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Design and implementation of a waterless solar panel cleaning system

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ABSTRACT

Manual cleaning of large solar installations is often labor-intensive and time-consuming, primarily due to the accumulation of dust on solar panels, which significantly impairs their efficiency. The study introduces a novel, waterless, cost-effective automatic cleaning system for small solar panels. The rationale behind this innovation stems from the necessity to mitigate efficiency losses caused by dirt and contaminants on solar surfaces. The automated system employs an Arduino microcontroller enhanced with a real-time clock to optimize cleaning schedules based on environmental conditions. The system consists of a two-stage mechanism which includes an ejector blower that produces a strong air jet, complemented by a flexible brush that effectively removes dust as well as sticky dirt. Cleaning intervals are strategically determined to ensure consistent maintenance without manual intervention, thus maximizing energy output. Tests on a 60 W solar panel revealed an impressive average power output increase of 26.23 % following cleaning. This prototype demonstrates the efficacy of the cleaning approach and underscores its potential to alleviate efficiency losses attributed to dust accumulation. Particularly advantageous in arid regions where water conservation is paramount, this automated system enhances energy production and operational efficiency for solar plant operators, promoting sustainable energy practices.

1. Introduction

Electricity demand is rising exponentially due to increasing population density, driven by rural-urban migration, rapid urbanization, and economic growth. It is essential to note that in many developing countries, rural areas lack consistent access to electricity [1,2]. The complexity of the landscape in remote areas makes it challenging to design and implement rural electricity networks [3,4]. Electricity affordability is a significant concern in rural areas. Low incomes and greater distances result in power losses and higher costs for consumer service and device maintenance, leaving many villages in developing countries unelectrified [5]. Solar energy, with its high potential, particularly in sub-Saharan Africa and the Global South, offers a viable solution to rural electrification challenges [6].

Mono-crystalline photovoltaic (PV) panels use only 15–18 % of the sun's rays to generate electricity under standard test conditions [7]. It is a problem to attain optimum efficiency due to low insolation, high air mass, and increased temperature. Sun rays contain build-up of contaminants such as dust, bird droppings, and snow [8]. The build-up of dust on the surface of the PV panels can significantly reduce power output by 6–45 % and efficiency by 13–38 % compared to clean modules [9]. The regions with the highest dust levels such as the Middle East, losses vary between 10 % and 70 % [10]. So, frequent cleaning of the panels is necessary to obtain the required power output from the panels.

The manual cleaning of solar panels has gone through several stages. Numerous firms offer a panel cleaning service to restore its required performance [11]. The used traditional cleaning methods involved manual scrubbing with soft brushes, water, mild soap, and low-pressure washing machine. Traditional cleaning is associated with drawbacks such as the risk of accidents to personnel, difficulty in moving, damage to panels, and higher costs [12]. In Jordan, manual cleaning using a brush and wipers costs 21 to 26 € per panel per year, while an automated system costs 1.5 €annually per panel [13]. This automatic solar panel dust cleaning system addresses the challenges posed by manual cleaning

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while providing efficient, non-abrasive clean-up and avoiding the interruption in performance caused by dust build-up [14,15].

Recently, the cost implication and non-availability of water in some regions have limited the widespread use of electrostatic and aqueous solar panel cleaning systems. Dry cleaning is a low-cost, independent solution that does not rely on a water supply in areas where rainfall is scarce [16].The combination of air jets and brushes ensures more thorough cleaning than systems using only one method, which is particularly beneficial for panels subjected to a wide variety of dust types. The design minimizes the need for frequent maintenance, with only periodic brush replacement and system checks required to ensure their performance over time. This makes it suitable for small and medium-sized solar installations where manual intervention may not always be feasible. In this study, we designed an efficient automatic waterless solar panel cleaning system for small PV arrays using Arduino uno microcontroller, real-time clock, air blower, and brushes.

1.1. Aim and objectives

The study aimed to design and implement an automated cleaning system for solar PV panels. The objective of this research is to achieve the following.

i. Replace the manual cleaning system with an automatic type.
ii. Reduce the energy lost from solar panels due to dust build-up.
iii. Make the cleaning of the solar panel simple and automated, reduce the cleaning cost of the cleaning process, reduce labor cost, and reduce time for the cleaning.

1.2. Significances

The importance of this research on the soiling problem demonstrates that solar panels require a complete cleaning process in operation to collect the most possible energy. The study sought to develop an automated cleaning system for solar panels with increased efficiency and high energy output, reducing the cost, cleaning time, and risk of operator injury in a high-voltage environment. The scope of this study is limited to one solar module, unlike arrayed solar modules that need additional resources. While focusing on one solar module for detailed analysis, the study could also consider the implications and potential scalability of the solution to larger solar arrays. This approach would position the present study as a stepping stone towards more comprehensive solutions.

1.3. Related works

The effect of accumulated dust on the performance of solar PV panels has been the subject of several research studies. El-Wahab et al. [9] examined the impact of varying dust densities (6–24 g/m2) on outdoor photovoltaic (PV) module performance. Increased dust accumulation correlated with lower front-side temperatures but higher backside temperatures, resulting in reduced output power (6–45 %) and efficiency (13–38 %) compared to clean modules. The findings underscore the necessity of regular maintenance to mitigate efficiency losses due to dust accumulation, with equations provided for calculating module efficiency and loss from dust.

Habib et al. [17] developed an Arduino-based solar panel cleaning system. The system addresses the problem of dust accumulation on solar panels using an exhaust fan as an air blower and a wiper. It is waterless, economical, and automatic. This system is effective in desert areas and avoids wasting water. It is an efficient solution for cleaning solar panels, with experimental results showing the system can achieve an efficiency of 87–96 % with different types of dirt on the panel. Myyas et al. [13] explore an intelligent device that improves the performance of solar cells by self-cleaning, preventing temperature rise, recycling cleaning water, and harvesting rainwater. The results suggested that the new device can resolve cleaning difficulties, increase performance, and collect rainwater from solar cells scattered worldwide. This technology enhances the efficiency of solar panels and decarbonizes the energy industry.

Similarly, Dahoud et al. [18] designed an automated cleaning system for solar panels, focusing on solar street light applications to reduce human effort. The study adopted a GSM module for real-time operation. However, this system consumes lots of water and requires frequent maintenance. Furthermore, an advanced online mobile app was implemented based on the collected data to enable the user to monitor the performance. Maindad et al. [19] explored solar panel cleaning for solar street lights. Regular cleaning is essential to prevent dust accumulation and battery failure. The paper proposes a cleaning system using an ATmega16A microcontroller. The system reduces human effort, saves time, and increases efficiency. The system uses a GSM module for real-time monitoring, linear actuators for brush movement, and a pump for water cleaning. Another similar work by Khadka et al. [8] designed a prototype for a solar photovoltaic system that can clean panel surfaces. The system includes a mobile cleaning robot and a cloud interface, with a human-machine interface for remote monitoring using a sensing unit as remote monitoring. The system can clean dry dust on a demo PV module and is feasible for large-scale solar farms when attached to metal rail tracks on a long solar array. Makmee et al. [20] designed an innovative solar cleaning robot that utilizes a stretch sling on all four sides, aiming to solve the persistent issue of ensuring maximum efficiency of solar power systems. The robot simplified the cleaning process for large-scale solar panel setups by reducing the need for human labor, lowering operational costs, and providing greater flexibility for configuration. This unique four-side stretch sling system enables precise maneuverability and accurate positioning.

Patel et al.[21 [][][]developed electrodynamics shield technology and self-cleaning coatings on glass material. The process determined the electrode, optical transmission, and electrodynamics properties. Nevertheless, it turned out that this cleaning method was insensitive to the rate of removal of dust particles. Solar energy is crucial for addressing climate change, but a critical concern is the build-up of dust on the surface of solar panels. Ahmed et al. [22] Designed an automated monitoring and cleaning of PV panels using a visual inspection robot. The findings show that analyzing the color of the solar panels can identify the degree of dust and increase the efficiency for lightly, moderately, and heavily dusted panels. The robot can automatically monitor panel color and operate, demonstrating the potential of this approach for automatic panel cleaning and monitoring, and could lead to more efficient conversion of PV panels and reduced environmental impact.

Kawamoto [23] developed an electrostatic cleaning system for removing dust from dirty solar panels using high alternating voltage across parallel shield electrodes, creating an alternating electrostatic force. This causes particles to move between the electrodes, with some passing through the top electrode and descending. The technology effectively removes dust with high levels of cleaning by applying high voltage at a lower frequency. The low power consumption of the system increases the efficiency of solar panels. Serkan and Apak [16] review a theoretical analysis of the detachment phenomenon of dust particles in interaction with surface acoustic waves, considering adhesion forces and gravity effects. This study establishes the required conditions for removing dust particles from tilted surfaces of panels using surface acoustic wave interference. The study also conducts experimental studies on contaminated PV solar panels to demonstrate the effectiveness of the surface acoustic wave in cleaning the surfaces of the solar panels.

Wable et al. [22] established that conventional cleaning methods often result in water waste, especially in tropical regions with dust accumulation. A new method using brushes or wipers can save water or eliminate it. In the UAE, water plays a crucial role in producing electricity. This method is environmentally friendly and eliminates the need for human power. A robot utilizes brushes or wipers for solar panel

cleaning. The robot is self-charged, taking power from generated electricity. This approach is more environmentally friendly and sustainable.

From the above literature review, we noted the following.

- The implications of dust deposition on solar panel surfaces are extensively studied.
- All authors mentioned above agree that dust accumulation on the surfaces of solar panels leads to a decrease in the energy output produced by these solar panels.
- Manual cleaning and automated cleaning methods exist as fundamental cleaning techniques for solar panels.
- Automated cleaning methods are more efficient than manual cleaning methods.

This paper presented a novel concept based on a set time and season for efficiently cleaning solar panels without water. The system utilizes a two-step cleaning process to prevent water wastage. An air blower fan and a rolling brush are employed to remove dust from the panel's surface and clear off any remaining debris.

2. Materials and method

The automated cleaning system for solar panels reduces the process of cleaning dust from the surfaces of solar panels in a PV array. The automation and control operation uses the Atmega328P-Arduino Uno, interfaced with various input and output devices and sensors. Fig. 1 outlines the workflow of the solar panel cleaning system. It demonstrates a simple, energy-efficient, and software-controlled cleaning mechanism for solar panels.

The hardware implementation section of this project comprised various hardware devices and components. This section encompasses different units explained in Fig. 2.

2.1. PV module

Solar energy starts with the sun. The PV modules convert the sun into electrical energy used to power electrical loads. The energy delivered by the sun is composed of particles referred to as photons [24]. PV modules consist of several solar cells electrically linked together. These cells are composed of semiconductor materials such as silicon. Solar panels work based on the principle of the photovoltaic effect and provide a practical and effective method of producing electricity for engineering applications. DC output power under standard test conditions determines the efficiency of each solar panel. Some different dimensions of PV panels available on the market include standard sizes like 65 × 39 inches, 77 × 39 inches, and 81.2 × 39 inches. Additionally, there are custom sizes and shapes tailored for specific applications, such as triangular or circular panels.

2.2. Control unit

In the automated cleaning system, the control unit is the programmable unit controlling the operation and monitoring of the entire system. It conveys input from the dusting and measuring devices and sends output to the display and washing devices. Fig. 3 shows the main components of the controller.

The Arduino Uno is an open-source controller circuit based on the microchip ATmega328P microcontroller. The layout has digital and analog input/output pin sets connected to shields and circuitry. Because of its low price and small size, Arduino Uno is especially suitable for wearable electronics and low-cost robots used to drive parts of larger devices. Using Arduino Uno as the main component of the control unit makes the system simple and less costly. This unit also contains a command configured in the software implementation as an input pull-up. This command enables a user to set the cleaning interval and period for the operation of the cleaning system to be triggered.

Additionally, the control unit comprises two limit switches. A

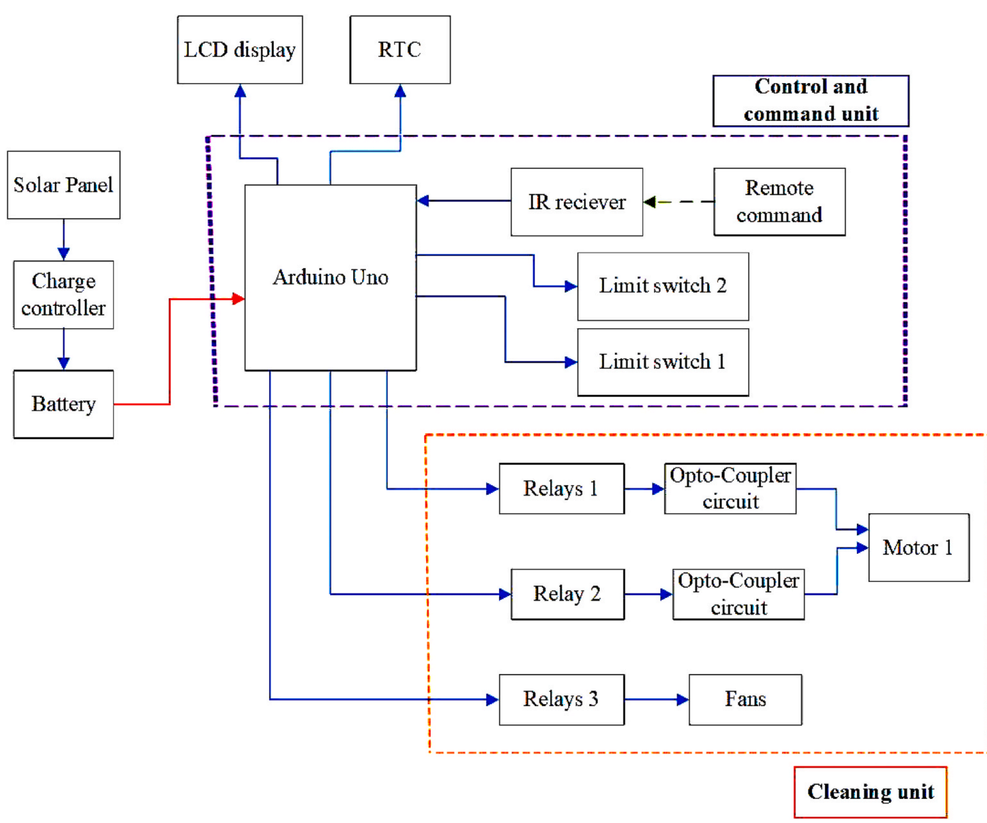

Fig. 1. Block diagram of the system.

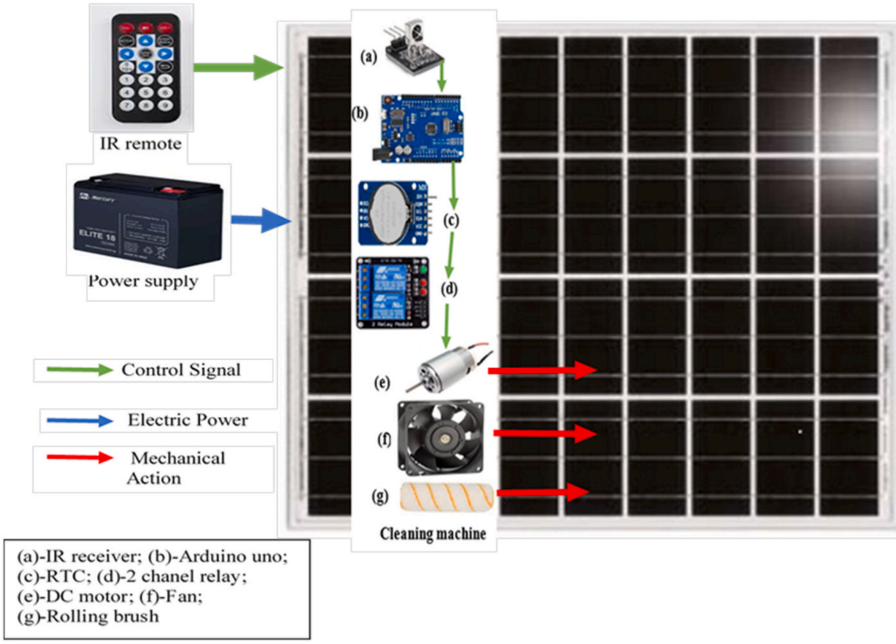

Fig. 2. Hardware devices and components.

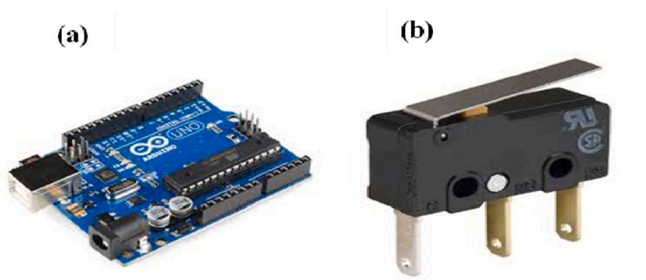

Fig. 3. (a) Arduino Uno (b) Limit switch.

proximity sensor is an electromagnetic device consisting of an actuator mechanically connected to a set of contacts. The limit switch is used in this project to detect the edges of the panel, enabling the mechanism to stop operating whenever the cleaning device reaches the edge of the solar panel.

2.3. Command unit

Infrared is a widely used and easily implemented radio link technology. TV/video remote controls, motion detectors, and infrared thermometers are the most common examples in everyday life. Infrared radiation is a form of light similar to the light we see around us. The frequency and wavelength are the only differences between Infrared and visible light. Infrared radiation is invisible to the human eye and exists outside the range of visible light. The infrared unit contains our remote configured in the software implementation as input pulled up in Fig. 4. This remote enables a user to set the time interval for the operation of the cleaning system to be triggered.

2.4. Real time clock (RTC)

Fig. 5 shows the real-time clock (RTC) module for time-keeping. The RTC is an IC and battery module that Keeps track of time and date without receiving external data. This data logger version uses the DS1307 RTC, I2C serial communication, 5VDC operating voltage, and 3VDC internal battery.

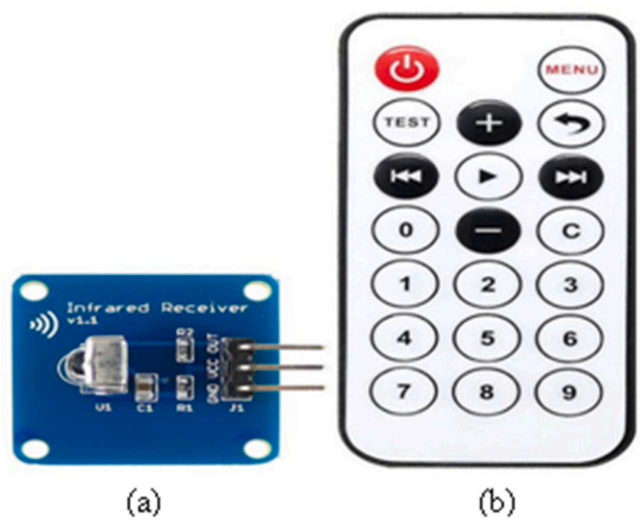

Fig. 4. (a) Keyes IR receiver; (b) Remote command.

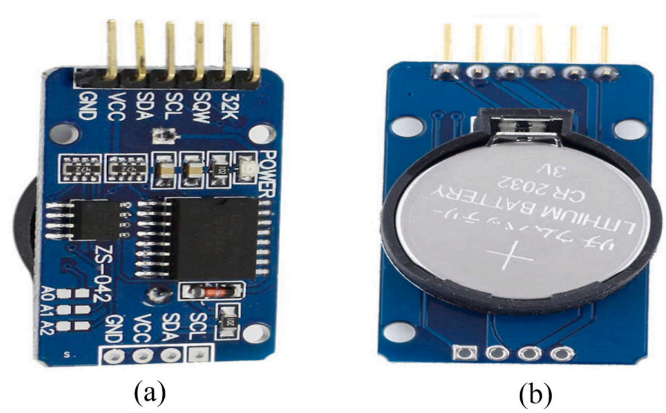

Fig. 5. (a) front view of RTC module; (b) back view of RTC module.

2.5. LCD display

Fig. 6 depicts the schematic and physical presentation of the LCD. LCD is a form of electronic display module used in circuitry and appliances such as computers, mobile phones, and televisions. The main benefits of this module are its small cost, programmable in principle, and activities. The LCD shows the cleaning status of the panel.

2.6. Cleaning unit

This unit is responsible for removing dust and debris off the surface of the solar panel. The requirement entails cleaning an entire row of solar panels in a PV array efficiently utilizing low energy without water. This unit performs its cleaning operation at all times. The cleaning method finally chosen contains both a brush and two fans. The different components of the cleaning unit are the DC motor, fans, and brush. Fig. 7 represents the unit responsible for removing dust and debris off the surface of the solar panel. The requirement entails effectively cleaning an entire row of solar panels in a PV array using a small amount of solar energy without water. The decision made for the design of this unit was the selection of the cleaning method. The cleaning method finally chosen uses both a brush and a fan. The different components of the cleaning unit are a DC motor, fans, and a brush. The role played by the DC motor in this unit is to provide the necessary mechanical power required to move the wiper across the panel surface.

The role played by the Fans in this unit is to generate air blows during the cleaning process to blow off the sand from the surface of the solar panel. Cleaning requirements for solar panels solely depend on the installation site and require individual decisions for each solar photovoltaic system. The following factors are essential when choosing the most appropriate cleaning device for solar panels.

- Yearly climatic conditions (rain, moisture, dew, wind, and the surrounding temperatures) of the site.
- Soiling type.
- In the case of anthropogenic pollution, busy roads, a big city, or industrial sites can increase the level of soiling. Agriculture and farming typically impact the environment and soil. Seasonal effects such as pollution can also be affected by sowing.

In this study, we used a soft brush attached to our moving engine. The brush is responsible for scrubbing and cleaning away accumulated dust from the surface of the solar panel. Cleaning solar panels by blowing off air alone cannot remove enough accumulated dirt, requiring additional cleaning using a brush. The brush rotates on itself to maintain a good rubbing on the panels' surfaces. We chose a wiper for this system implementation due to its availability and cost-effectiveness.

2.6.1. Moving engine

Before designing a moving engine, we first tried screw rods. We had negative results at the end, including too much noise due to vibration and high rotational speed of the DC motor and instability leading to the bending of the screw rods. Given the negative result on rods, we experimented with moving engines, recording a stable engine with excellent properties such as high load-carrying capacity, ease of design into a system, very little maintenance, and Smooth operation. In this project, the moving engine moves the brush and fans in translation across the panel surface. As the motor rotates, the engine moves as well. We designed the prototype for cleaning a single solar panel. For the system, we ensured the cleaning shaft covered the diagonal of the PV array for adequate cleaning of the entire row of a PV array.

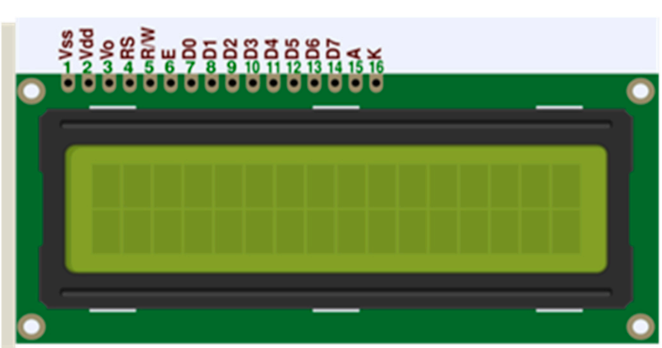

Fig. 6. Physical presentation of the LCD.

2.7. Software implementation

As earlier mentioned, we adopted a programmable microcontroller board (Arduino) to perform the designed automated cleaning system. Therefore, Arduino requires computer programming to aid the operation. We also adopted Proteus 8.10 for the simulation.

2.7.1. Circuit simulation

Circuit simulation involves creating and analyzing an electronic circuit model with software tools to predict and test circuit behavior and performance. Integrated circuits are expensive and time intensive. Proteus remains a faster and more cost-effective circuit simulator for testing circuit behavior and performance because of its simplicity and ease of use for digital simulations. Fig. 8 depicts the electronic circuit diagram designed and simulated with Proteus and used for implementing our system.

2.7.2. Operation of the system

This automated cleaning system for solar panels helps to facilitate the process of cleaning dust from the surfaces of solar panels for all photovoltaic installation applications. For this design, we have developed a cleaning device that moves along the length of a solar panel and can move on to clean an entire row of solar panels in a PV array. The simplicity and the low maintenance requirement of the designed solar panel cleaning system contributed to its choice. The cleaning device moves across the panel surface due to the moving engine system powered by the DC motor. The entire cleaning unit operates by the control unit, which receives signals from the command unit. The infrared remote controls the period and interval of cleaning, making this design simple and less costly. RTC helps in setting up the cleaning process. The Arduino receives the signal from the RTC and triggers the cleaning unit when the cleaning time has reached.

When the cleaner actuates the limit switch at the end of the solar module, the movement of the brush and the motor reverses backward. The engine stops and continues when the cleaner activates the limit switch at the other end of the solar panel. The flowchart in Fig. 9 summarizes this operating principle, starting from initialization and setting the cleaning period. The cleaning duration is displayed on an LCD, followed by validating parameters before activating the cleaning mechanism. The system employs a blowing fan and motorized apparatus, reversing direction upon triggering limit switches, and continuing until the cleaning cycle concludes, crucial for enhancing solar panel efficiency in arid regions.

The system is configured for cleaning, such as for June 20, 2024, between 10:00 a.m. and 12:00 noon, the cleaning process will be initiated once the specified period is reached. During the process, the system will operate in a cyclical manner, performing forward and backward movements until the cleaning period concludes. If the designated month, day, or time has expired, and a valid command is received, the system will activate another cleaning function. Conversely, if a command other than a cleaning directive is received, users are still permitted to modify the settings to establish their preferred cleaning schedule.

After carrying out the circuit simulation, the circuit was realized and tested on the PCB produced. The entire setup was then mounted on a

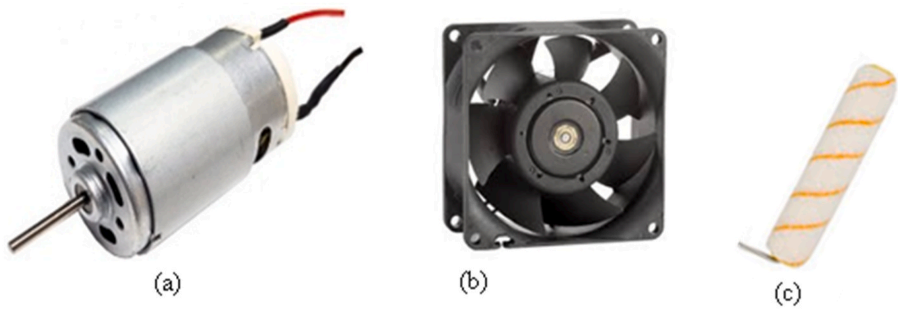

Fig. 7. (a) Dc motor (b) Dc fan (c) Rolling brush.

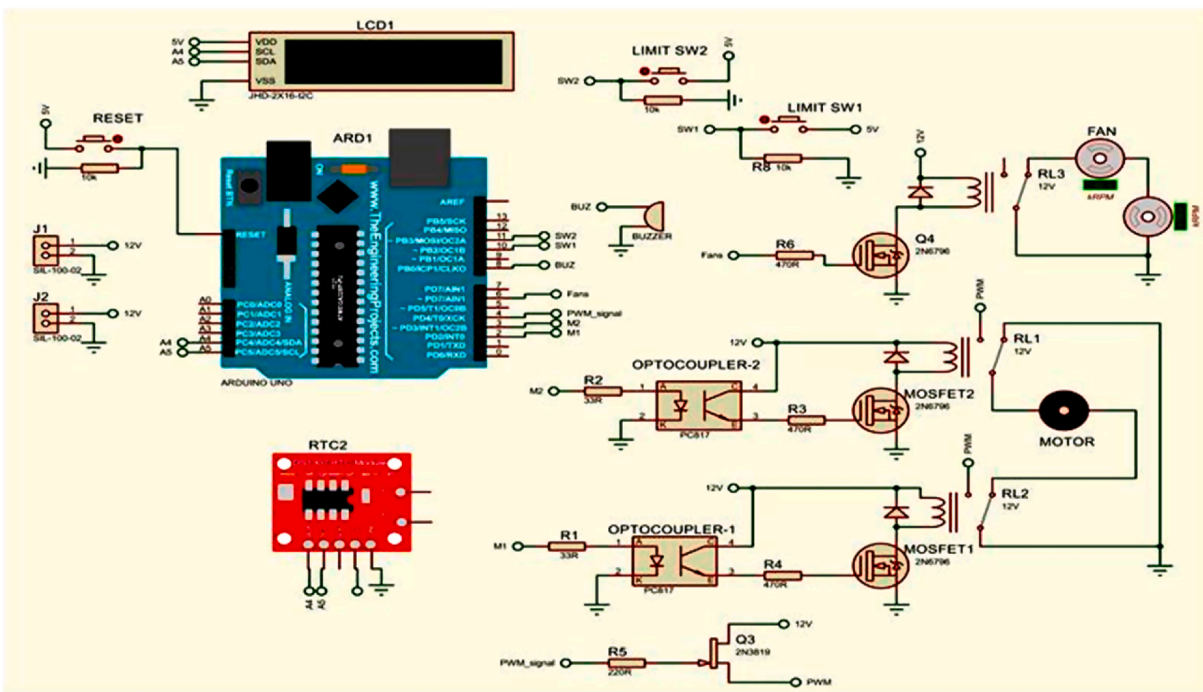

Fig. 8. Electronic circuit diagram.

wooden frame, providing a moving part of the cleaning shaft. Fig. 10 shows the implementation of the designed automated cleaning system for solar panels in a PV array. This system is powered by a rechargeable battery directly charged from the solar panel. This system can be implemented on a small solar panel, facilitating the cleaning process and reducing human involvement in the cleaning process. The tested prototype demonstrated effectiveness.

3. Results and discussions

3.1. Results

The efficiency of the automatic solar panel cleaning system were assessed in two modes: by evaluating the dirty modules before and after cleaning. Additionally, the system was combined with a dust-cleaning system to enhance solar insolation. We conducted measurements of peak voltage, current, and power values on both the dusty and cleaned panels over a two-day period between 10 a.m. and 12 noon, considering the high intensity of sunlight.

3.1.1. Measurements on the dusty solar panel

Current and voltage measurements were carried out on the dusty solar panel to determine the voltage and current of the solar panel at maximum power, applying 60 g of dust on the surface of the panel and measurement are taken at 30 min interval to have several readings.

Table 1 and Fig. 11, shows measurements for a dusty solar panel, we observe a general upward trend in voltage, current, and power over time, with each parameter gradually increasing from 10:00 a.m. to 12:00 p.m. The voltage starts at 14.69 V and rises to 14.99 V, while the current grows from 1.59 A to 1.80 A, leading to an increase in power from 23.36 W to 26.98 W. This incremental improvement corresponds to the rising sunlight intensity, which provides more energy for the panel to convert into electrical power. However, the dust layer hampers full solar insolation, reducing overall efficiency. The highest power values are recorded at noon when sunlight is at its peak, reflecting the direct relationship between solar irradiance and panel output. Although the dusty panel sees some performance gains with increased sunlight, the presence of dust limits the full potential of the solar panel.

3.1.2. Measurements on the clean solar panel

Table 2 and Fig. 12 reflects measurements from a clean solar panel, showing a higher overall performance compared to the dusty panel: The voltage starts at 15.40 V at 10:00 a.m. and peaks at 16.61 V at 12:00 noon, while the current grows from 1.91 A to 2.08 A, leading to an increase in power from 29.41 W to 34.55 W. The trends mirror those of the dusty panel but at significantly higher values. The absence of dust allows

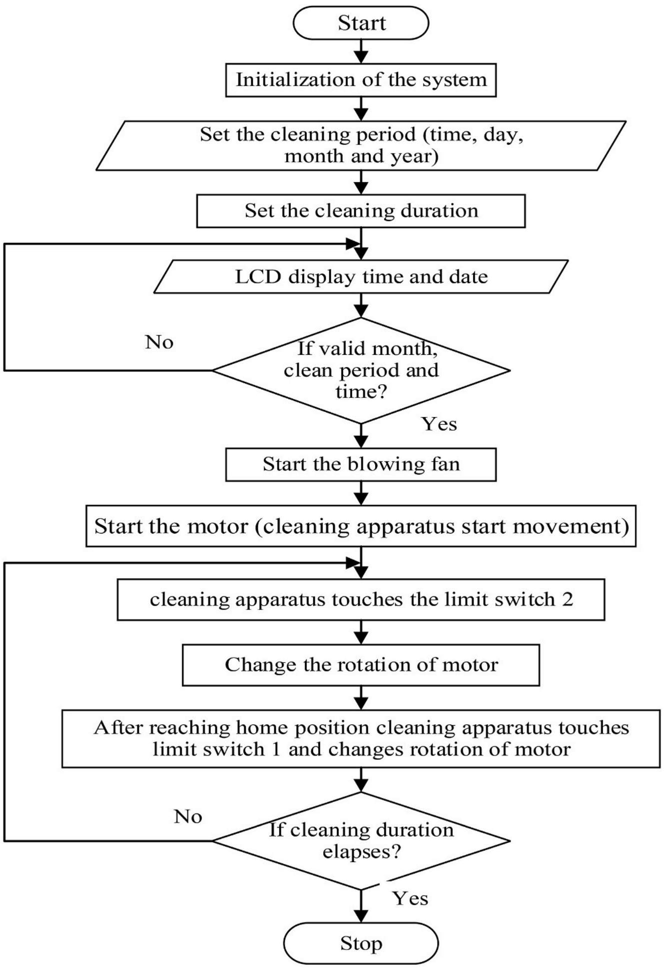

Fig. 9. System flowchart.

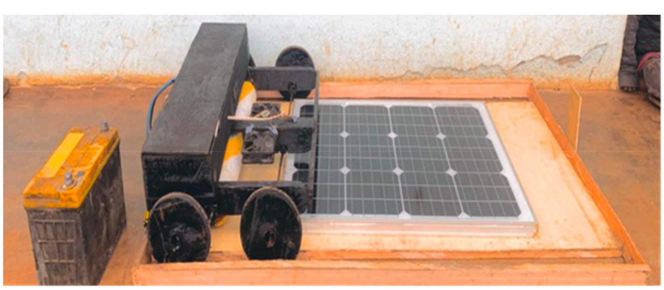

Fig. 10. Prototype of automated cleaning system for solar panels.

Table 1
Measurements on the dusty solar panel.

Measurement time	Voltage (V)	Current (A)	Power (W)
10:00	14.69	1.59	23.36
10:30	14.72	1.61	23.70
11:00	14.81	1.66	24.58
11:30	14.87	1.72	25.58
12:00	14.99	1.80	26.98

the panel to harness more solar energy, leading to enhanced performance. The current values show a significant increase, reflecting better electron movement within the photovoltaic cells when sunlight is unobstructed.

Table 3 illustrates the average increase in output power between the dusty and clean panels. The results showed an increase in the output power of the clean solar panels using our prototype. We calculate the average increase in output power using Equation (1).

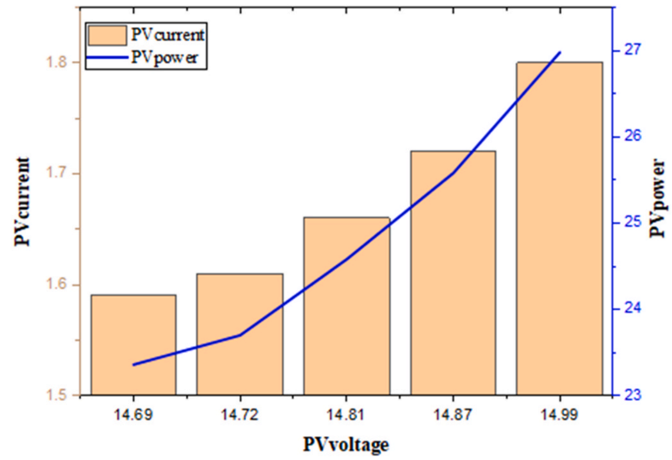

Fig. 11. PIV curves for the dusty solar panel.

Table 2
Measurements on a clean solar panel.

Measurement time	Voltage (V)	Current (A)	Power (W)
10:00	15.40	1.91	29.41
10:30	15.52	1.95	30.26
11:00	15.74	1.96	30.85
11:30	15.93	1.99	31.70
12:00	16.61	2.08	34.55

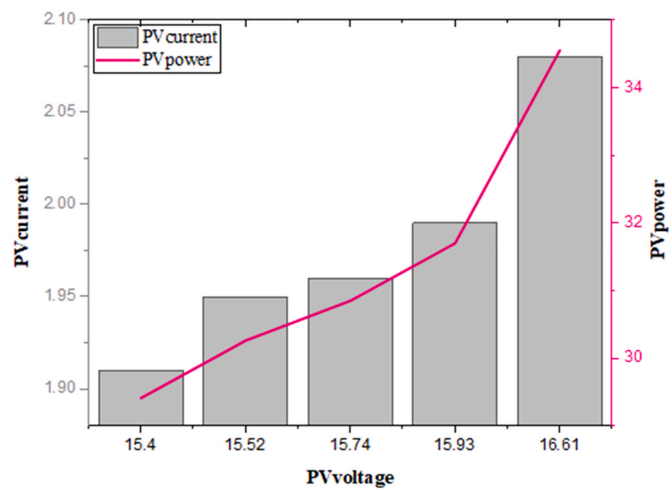

Fig. 12. PIV curves for the clean solar panel.

Table 3
Measurements of the average increase of output power.

Measurement time	Power from dirty panel (W)	Power from Clean panel (W)	Average increase of output power (Q)
10:00	23.36	29.41	26.23 %
10:30	23.70	30.26	
11:00	24.58	30.85	
11:30	25.58	31.70	
12:00	26.98	34.55	
daily panel power	124.2	156.77	

$$Q = \frac{dcs - dds}{dds} x\,100 \quad (1)$$

Where Q = Average increase of output power, dcs = daily power of cleaned solar panel, dds = daily power of dirty solar panel.

At 10:00 a.m., the dusty panel produced 23.36 W while the clean panel generated 29.41 W. By noon, the clean panel delivered 34.55 W, while the dusty panel reached only 26.98 W. These numbers emphasize the significant reduction in energy capture caused by dust accumulation. The total daily power generated by the clean panel was 156.77 W, compared to 124.2 W for the dusty panel, reinforcing the necessity of regular cleaning for maintaining optimal panel performance. Fig. 13 highlights comparison of PIV curves for the dirty and clean solar panel.

Analyzing Fig. 13, it becomes evident that the power output of the solar panel system showed a consistent upward trend following each cleaning session. This trend indicates that cleaning the solar panels had a beneficial effect on their overall efficiency and performance. Notably, there was a significant spike in power output immediately after cleaning, with the power output peaking at 34.55 W, as opposed to the initial 26.98 W. This sharp increase strongly suggests that the presence of accumulated dirt or debris on the panels was hindering their ability to capture sunlight radiation effectively. The subsequent cleaning of the panels resulted in a substantial improvement in power generation, underscoring the importance of regular maintenance and upkeep of solar panel systems.

3.2. Discussion

The results from the performance evaluation of the developed automatic solar panel cleaning system provide significant insights into the critical role of panel cleanliness in optimizing solar energy capture. The comparative analysis between the dusty and cleaned photovoltaic (PV) panels reveals a compelling narrative about the impact of environmental factors on solar energy generation. The systematic approach adopted in measuring the peak values of voltage, current, and power before and after cleaning services underscores the necessity of maintaining solar panels. The PIV curves presented in Figs. 11 and 12 show the relationship between these parameters for dusty and clean panels. The clean panel consistently demonstrates higher power output across all voltage levels, as shown in Fig. 13, which compares both curves. In Fig. 11, the dusty panel exhibits a gradual rise in power but fails to reach the levels seen in Fig. 12 for the clean panel. This is due to the dust obstructing sunlight.

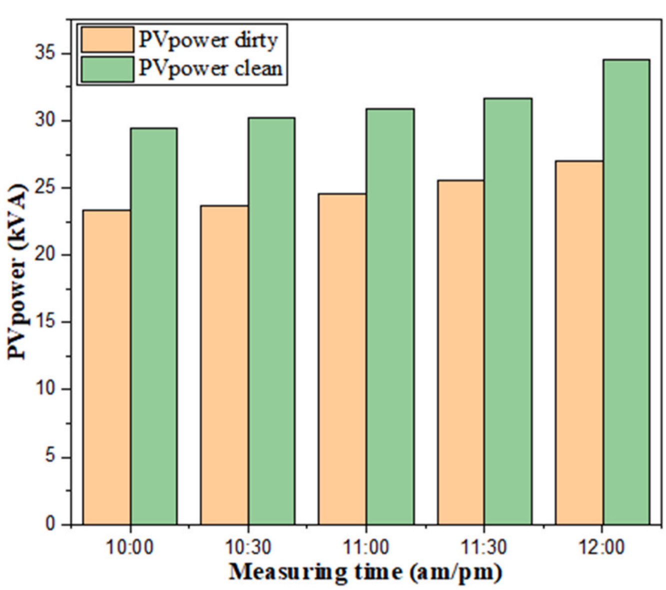

Fig. 13. Comparison of PIV curves for the dirty and clean solar panel.

In Fig. 12, confirming the positive impact of dust removal on solar panel efficiency, the clean panel achieves much higher power levels. In Fig. 13, the comparison of the two panels further illustrates the performance gap and highlights the fact that a clean panel is able to produce 26.23 % more power than a dusty panel. The data highlights the deleterious effect of dust on solar panel efficiency. The accumulation of dust particles on the surface reduces the absorption of sunlight and the overall power output. Over time, if the panels are not cleaned, the drop in performance becomes significant. This explains the need for the proposed waterless cleaning system, capable of maintaining cleanliness without using water - a crucial advantage in dry areas where water supplies are scarce. The upward trends in the clean panel's performance highlight the benefits of frequent cleaning, which can maximize power generation throughout the day. This 26.23 % increase in power output post-cleaning is striking and aligns with similar findings in the literature. Hammoud et al. [25] reported that minimal dust accumulation hampers solar panel efficiency, leading to a 30 % decrease in energy production. The impact of dust on the module's performance is evident when comparing the data from Tables 1 and 2, showing a noticeable reduction in system output. However, cleaning the solar panel surface increases the voltage and current. This results in a higher power output. This relationship underscores the direct impact of surface conditions on solar panel performance. The findings align with previous research by Eiche et al. [26], emphasizing the effectiveness of maintenance strategies in improving energy efficiency.

In Fig. 12, the findings consistently demonstrate effective cleaning of the solar panels, improving their capacity to capture solar energy. The effective removal of barriers that block sunlight increases the power output, enabling better absorption of photons and energy conversion rates. Notably, the current exhibited a more marked increase at higher voltages, indicating that the cleaning process enhances operational efficiency as voltage levels rise. This discovery aligns with Qin et al. [27], which highlighted the correlation between the effectiveness of PV systems and the cleanliness of their surfaces, pointing out that ideal performance depends solely on light conditions and cleanliness.

The broader implications of these results extend to the design and construction of solar panels, particularly in arid and semi-arid regions where dust accumulation is a frequent challenge. The waterless cleaning system presents a sustainable solution to maintaining solar panel efficiency without the need for substantial water resources, which are often scarce in several regions. Makani et al. [28], supports the notion that such innovation promotes environmental sustainability, aligning with global efforts to optimize resource use in renewable energy technologies. Cleaning the solar module with our system is performed automatically based on the installation area and the climatic season, minimizing human involvement in the cleaning process. Al-Housani et al. [29]performed experimental research on different cleaning methods for solar panels in arid climates. They discovered that panels cleaned regularly with mechanical systems outperformed those cleaned manually or less frequently. This supports the current study's emphasis on a waterless mechanical system to maintain efficiency. Table 4 compares the performance of the proposed system with other waterless and automated solar panel cleaning systems based on key metrics such as efficiency gain, and ease of implementation.

This comparison highlights that the proposed system offers competitive efficiency and straightforward implementation and maintenance requirements. It strikes a balance between ease of use and performance, making it ideal for small and medium scale installations.

3.2.1. Cost estimation analysis

The expenses for cleaning PV systems are influenced by the frequency and practicality of removing dirt and snow from the panels. These costs are evaluated based on research, design, and construction phases. Initially, research includes a comprehensive literature review and component identification. Design tasks involve system

Table 4
Performance comparison with other systems.

System Type	Efficiency Gain	Ease of Implementation	System Remarks	Ref
Proposed waterless cleaning system	26.23 %	Easy to implement, requires low maintenance	Combines air blower and brush, making it highly effective in dry and dusty conditions.	
self-cleaning PV sliding system	6.4–18.3 %	Moderately complex, employing rollers, motors, sensors, and brushes for automatic cleaning twice daily.	System significantly enhances efficiency throughout all seasons, safeguarding against dust deposition and hailstorms.	[30]
Automated IoT-based cleaning system	32 %	Initial installation process is moderately complex and requires technical expertise.	Effective in real-time dust removal, easily controlled remotely, and reduces manual labor.	[31]
Automatic Dust Wiper	43.37 %	The implementation process is straightforward,	Significant improvement in solar panel performance in dusty environments, reduces heat buildup, making it highly effective for areas with frequent dust accumulation	[32]
Vacuum blower-based cleaning	18–20 %	The moderate complexity employing a cart-mounted vacuum blower system for dust removal.	Water-free, making it ideal for arid regions where water conservation is crucial. Reduces manual cleaning costs and labor.	[33]
Automatic cleaning system	30–35 %	**Less complex, it** uses DC motors, light dependent resistors, and a water pump	Highly effective in maintaining panel alignment and cleanliness, suitable for large solar farms.	[34]

conceptualization, schematic creation, and Arduino integration. Construction involves procuring components, system assembly, and prototype testing. Table 5 provides the cost estimates for the system's design and construction. The total cost of a single system, including materials and research, is $72.60, calculated based on market prices at the time of system development. Scaling up to larger solar installations would only slightly increase the cost, as the control system can manage multiple panels.

Table 5
Cost estimation of the proposed system.

Components	Cost (dollar)
Solar panel 60w	18.48
Arduino Uno	4.27
DC gear motor	2.12
Motor driver circiut	2.31
Wheels	1.47
Rolling brush	1.85
Remote command	0.94
Fan (air blower)	1.79
Buck boost converter	2.35
Display unit lcd	1.97
Real time clock	1.58
Frame	3.47
System construction	12
Research cost	18
Total	72.6

3.2.2. *Cost-benefit analysis over the lifetime of the cleaning system*

Beyond the upfront costs in Table 5, assessing the long-term economic benefits of the automated waterless solar panel cleaning system is crucial. The analysis includes both initial and operational costs over the system's lifetime, and energy efficiency improvements achieved by regular automated cleaning.

Firstly, regarding initial cost, the proposed automated system initial installation cost of the is $72.60 per panel. In contrast, manual cleaning services can cost between €21–26 per panel annually [13]. The automated system incurs minimal operational costs, primarily related to periodic brush replacements and minor maintenance, estimated at $9.50 per panel per year Assuming a conservative lifespan of 10 years for the automated system the total operational cost approximately $95, while the total cost for manual cleaning would be approximately €210 to €260 per panel over this period.

Secondly, dust buildup on solar panels can lower energy output by 6–45 %, with losses as high as 70 % in places like the Middle East [10]. The automatic cleaning method improves solar panel performance by an average of 26.23 % following the cleaning thereby producing an extra 15.66W of power which translates to 28.47 kWh of energy annually, that is a total of 284.7 kWh over a 10-year period, if the panels are used for an average of 5 h each day.

Thirdly, the proposed system eliminates the need for human labor, reducing the associated costs and safety risks, particularly in high-voltage environments. Also, unlike traditional methods that require significant amounts of water, especially in arid regions, this system is completely waterless, contributing to environmental sustainability.

3.2.3. *Expected maintenance frequency and technical issues*

The waterless cleaning system designed for solar panels, featuring both an air blower and a flexible brush, requires regular maintenance to maintain optimal performance. The brushes, which effectively remove dust from the panel surfaces, are subject to wear over time, particularly when dealing with coarse or abrasive dust particles. Drawing from insights on similar systems, it is expected that brush replacement will be necessary every 3–4 months, influenced by cleaning frequency and environmental factors—such as harsher conditions in desert or coastal areas that may accelerate wear.

Additionally, the air blower components should be inspected every 4–6 months to avoid dust buildup in the jets, which could diminish airflow efficiency. Continuous mechanical movement can lead to the wear and tear of the brushes, ultimately reducing cleaning effectiveness. To prevent premature failures, regular lubrication of moving parts like the DC motors is recommended. Furthermore, components such as sensors (including limit switches) and the Arduino controller may encounter connectivity or calibration issues. Conducting routine system diagnostics will aid in identifying and addressing these problems before they result in system downtime.

3.2.4. *Limitations and challenges*

The proposed system offers several benefits but also faces challenges, particularly in diverse geographical locations and climates. In areas with extreme weather, such as heavy snowfall or high humidity, the air blower may struggle with contaminants like snow, mud, or bird droppings. Additional cleaning mechanisms, such as heating elements or stronger jets, might be necessary for improved effectiveness in these climates.

While the system effectively handles dry dust, it may struggle with sticky or oily dust common in industrial areas or near oceans, which could limit its efficiency without supplementary cleaning methods. Prototype testing revealed that the current design generates unwanted vibrations and noise due to brush and fan movement, affecting long-term operational stability and brush performance. Although the

system works well for small setups, scaling up to larger photovoltaic (PV) arrays may require more robust designs and additional power sources to ensure effective cleaning over wide areas. Addressing these challenges could lead to future research and development opportunities, focusing on enhancing the system's versatility and robustness across various environmental conditions.

4. Conclusions and recommendations

4.1. Conclusions

Dust accumulation on solar panels significantly reduces power generation, prompting the design of a waterless cleaning mechanism, which integrates an air blower and brush into a single automated solution. Unlike other methods that rely on water or electrostatic forces, this system effectively removes dust without the need for water—a critical factor in arid regions where water resources are scarce. This project delivered a versatile cleaning solution tailored for various photovoltaic systems, with key components including a fully automated mechanism for photovoltaic systems and specifically designed motor paths tailored to different solar panel configurations. While dry-cleaning is less effective, the combination of air jets and brushes ensures more thorough cleaning than systems using only one method, which is particularly beneficial for panels subjected to a wide variety of dust types. The experimental results demonstrated a remarkable improvement in solar panel efficiency, with an average power output increase of 26.23 % after cleaning. By keeping the panels free of dust, the system increases both the life and effectiveness of solar installations. This significant enhancement underscores the effectiveness of our approach, highlighting how the automated system can achieve substantial results even without wet cleaning. The system's cost-effectiveness and adaptability make it suitable for different types of solar panels, addressing a critical need in solar energy maintenance. By combining innovative technology with practical applications, this project not only improves the performance of solar panels but also contributes to environmental sustainability by eliminating water usage for solar panel cleaning initiatives in regions facing water scarcity, promoting solar energy as a more viable and eco-friendly option.Overall, the developed automated cleaning system represents a crucial advancement in maximizing solar energy output while minimizing operational costs.

4.2. Recommendations

This waterless automated cleaning method for the cleaning of solar panels has proven to be more effective and less time-consuming than manual methods. Therefore, solar energy operators in small, medium, and large photovoltaic installations can adopt this automated cleaning method. Automated cleaning methods are easy to implement, consume less energy, and are waterless. Therefore, to overcome the challenges posed by dust accumulating on solar panel surfaces, we recommend our automated cleaning system as an effective solution for implementation. Implementing this system will go a long way in enabling solar users to maximize energy generation by solar panels.

4.3. Perspectives

This automated cleaning system cleans solar panels using a brush and fans. The brush and fans move horizontally across the surface of the solar panel. Consequently, this system can only clean a few rows of solar panels in a PV array. This system also causes unwanted results such as vibration, noise, and sticky dust that is difficult to clean. Therefore, to improve the performance of the system, we would like to make the following improvements.

- Replacing the wood broom handle with a 3D-printed plastic material could minimize the vibration and noise.
- To design a better brush to easily remove sticky dust from solar panels and avoid causing damage to the collector's surface.

CRediT authorship contribution statement

Charity M. Nkinyam: Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chika O. Ujah:** Writing – review & editing, Supervision. **Kingsley C. Nnakwo:** Writing – review & editing. **Obiora Ezeudu:** Visualization. **Daramy V.V. Kallon:** Supervision. **Ikechukwu Ike-Eze C. Ezema:** Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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